REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
	Technical Papers	

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 18 Apr 2001

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2001-091**
J.S. Shelley; R. LeClaire; J. Nichols; and D. Miracle (MLLM), "Yes this is Rocket Science: MMCs for Liquid Rocket Engines"

TMS Fall Meeting **(Statement A)**
(Indianapolis, IN, 05 Nov 2001) (Deadline 11 May 2001)

20020827 081

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Leilani Richardson
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	A		(661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

41 items enclosed

YES - This is Rocket Science: MMCs for Liquid Rocket Engines

04-08 Nov 01

J. S. Shelley

Materials Application Engineer

PRSE (Liquid Rocket Engines)

Air Force Research Laboratory

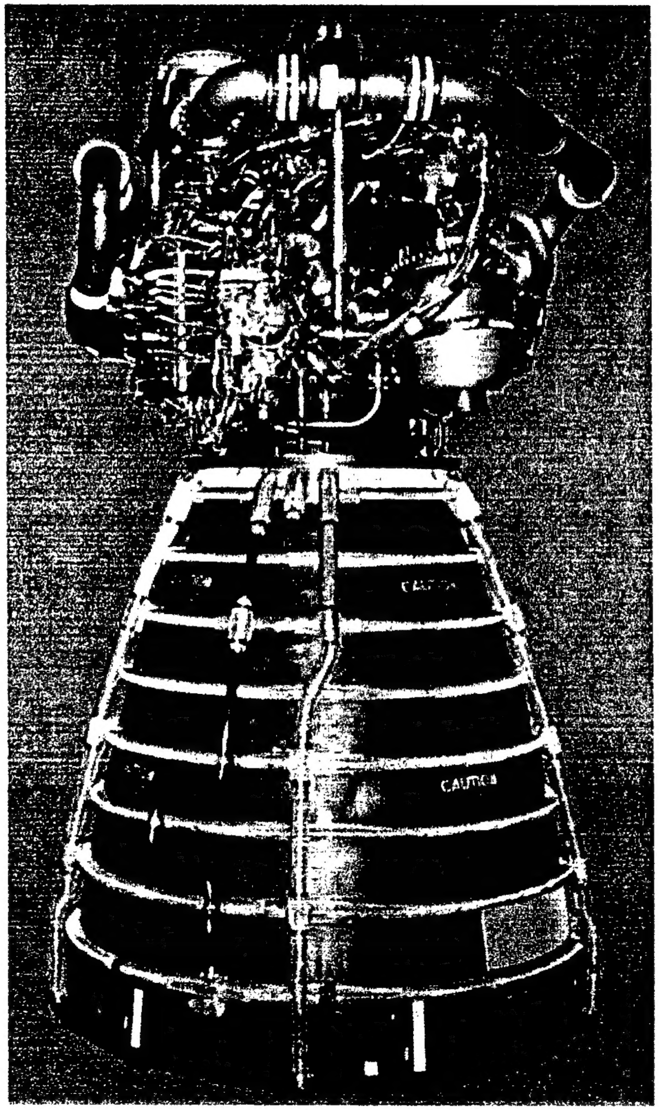
Overview

- What is Affordable?
- Affordability goals and IHPRPT
- IHPRPT Phase II Technologies
- MMC projects for IHPRPT Phase II
- Summary

What is Affordable?

- Low production rates
  - 1 SSME produced per year, 50 total
    - 3 major upgrades since 1980 (1988, 1995, 1999)
      - Over 6400 P&W F100 engines produced and in-service since 1974 in 3 models, 250/year
        - engine development cycle roughly 10-12 years
      - In 1996, US auto makers produced 11.8 M cars
        - new model development cycle 3-5 years
- Highly specific sub-components designs
  - few modular parts
  - labor-intensive assembly, refurbishment
- Performance cannot be sacrificed.

Space Shuttle Main Engine



Thrust	470,000 lbf
Weight	7,289 lb
Mission Duration	9 minutes
MTBO	7.5 hrs

Designed to 10 mission MTBR

105 in diam by 167 in long

3 SSMEs on Space Shuttle

What is Affordable?

- Most turbomachinery components machined from forged billets
  - 51% total engine weight, 42% total engine cost
  - high performance properties with low Cv, tight tolerances

Coefficient of variation

- Thrust chamber jacket Electrodeposited Nickel
  - 18% of C&ECD weight, 6.6% engine weight
  - 28% of C&ECD cost, 11% engine cost
  - 6 months to 1.5 year lead time
  - optimize shape, maximize liner/jacket bond integrity

Affordability Goals

- Integrated high Performance Rocket Propulsion Technology Program (IHPRPT) has established goals based on total system affordability
  - Engine performance
  - Reusability
  - Engine cost
- System level goals flowed down to component level goals
  - component goals can be traded off

IHPRPT

- Integrated High-Payoff Rocket Propulsion Technology program
  - – framework for guiding and tracking performance improvements
  - – DoD and NASA, headed by Air Force, 1995
  - – "materials" requirements tracked through IMWG (IHPRPT Materials Working Group), 1997
  - – 5 years into a 15 year program
    - 3 phases planned, 5 years each
    - each phase culminates in an engine demonstration

IHPRPT Goals

Cryogenic Boost and Orbit Transfer

	Phase I	Phase II	Phase III
Reduce Stage Failure Rate	25%	50%	75%
Improve I_{sp} (sec)	1%	2%	3%
Reduce Hardware Costs	15%	25%	35%
Reduce Support Costs	15%	25%	35%
Improve Thrust to Weight	30%	60%	100%
Mean Time Between Removal (Mission Life-Reusable)	20	40	100

All percentages

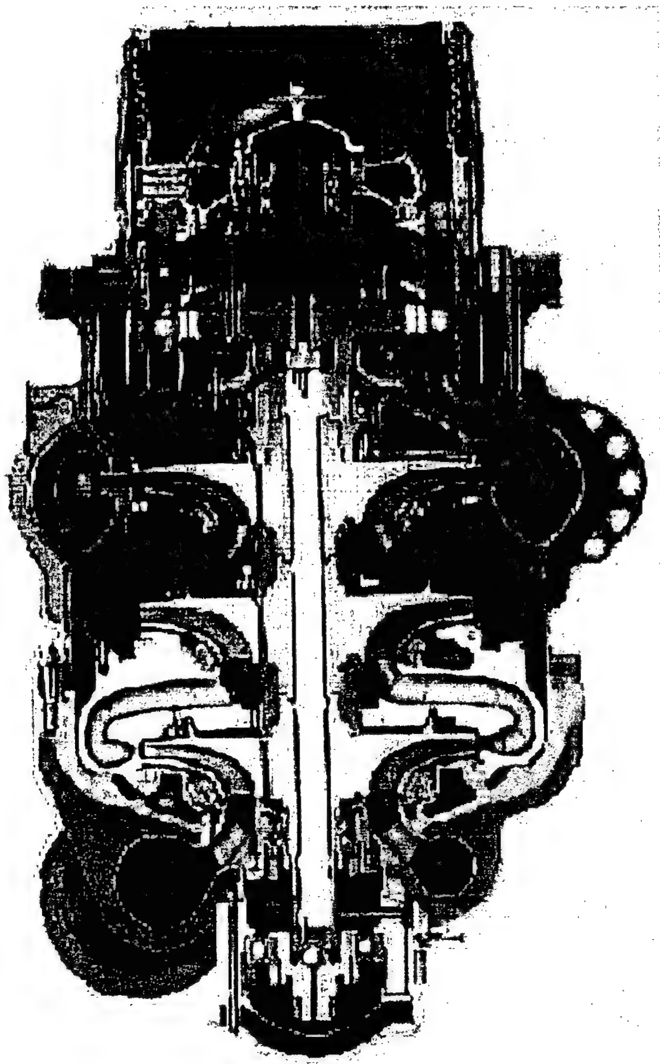
IHPRPT Phase II Technologies

- Accomplish goals by enabling engineering design changes
  - Full-flow engine cycle (closed)
  - Reduced number of pump stages
  - Increased combustion pressures
  - Higher area ratio nozzles

Phase II MMC Projects

- PMD
  - Near net shape processing
  - Al MMCs
  - “Nanostructured” Al
  - Oxygen compatible nickel alloys and MMCs
- C&ECD
  - Casting approaches to jackets
  - Transpiration cooling
  - Nozzle materials and design

SSME HPFTP



High Pressure Fuel Turbopump

- 75,000 Horsepower
- 178 lbs/sec fuel flow rate
- 6,900 psia discharge pressure
- 1,440 °F turbine temperature
- 37,000 rpm
- 3 stage pump/2 stage turbine
- 480 lbs (218 kg)
- roughly 30 in diam by 41 in long

“Materials” Requirements for Pumps

- High strength at cryogenic temperatures (125 ksi)
- LCF resistance and toughness at cryogenic temperatures
- Low density (0.14 lb/in^2)
- Compatible with cryogenic propellants
- Amenable to deterministic design methods
  - generally requires ductility at temperature above 3%
- Near-net shape processing of complex geometries

Z

Current Pump Projects

- Housings
  - particulate reinforced aluminum
    - 20 - 40% project weight savings, moderate risk, MRL = 3.5, PRL = 3
  - chopped fiber reinforced aluminum
    - 20 - 40 % -ΔW, mod risk, MRL = 2.5, PRL = 2
- Rotating components
  - high-strength, compatible alloys
    - 10 - 20% -ΔW, mod-high risk, MRL = 2, PRL = 5
  - ‘nanostructured’ Al
    - 0 - 10% -ΔW, mod-high risk, MRL = 2.5, PRL = 1

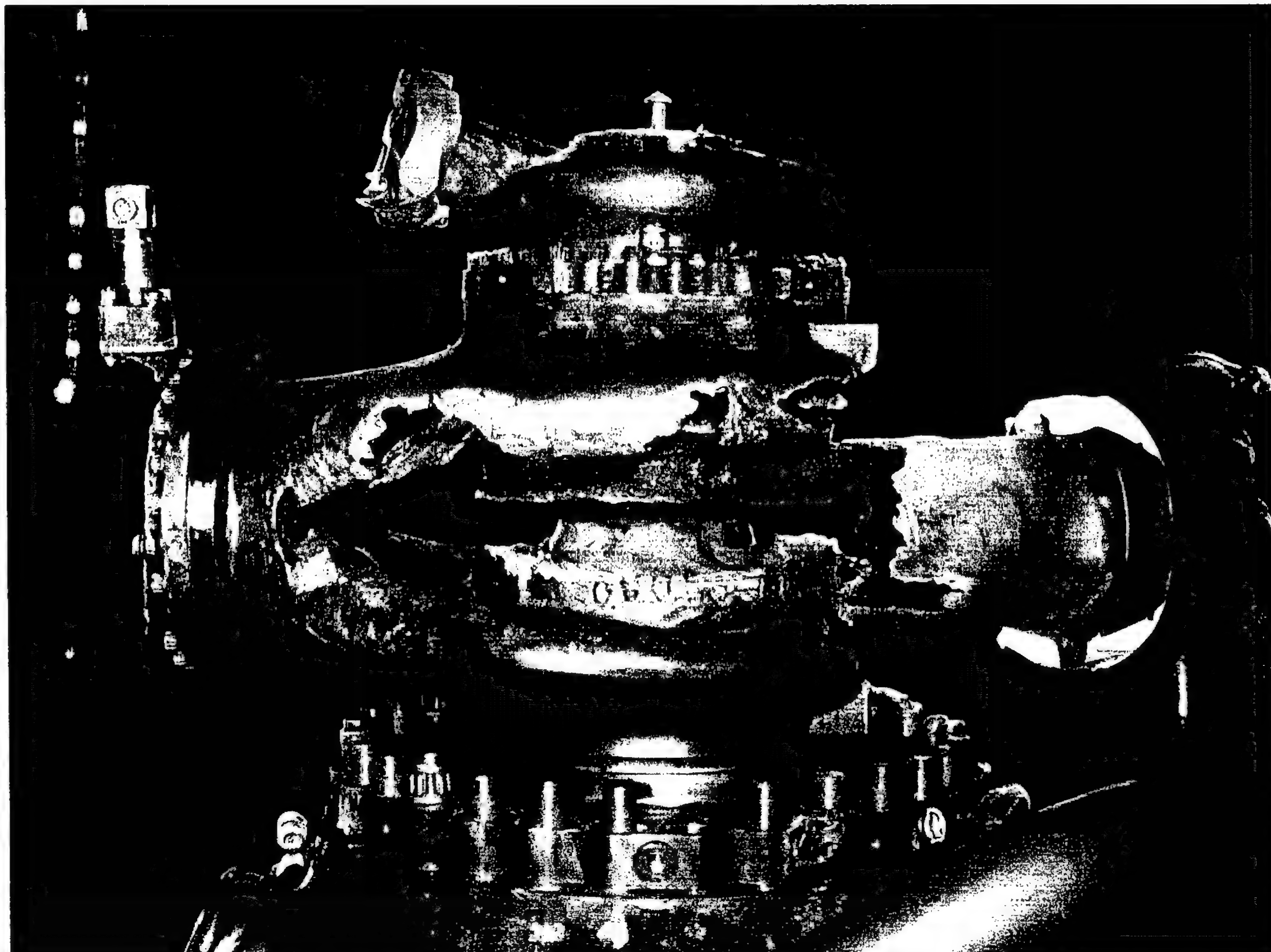
Future Pump Efforts

- Future Efforts
  - ‘functionally graded’ MMCs with continuous fiber constituents
  - CMCs for rotating components
  - PMCs for housings

“Materials” Requirements for Full Flow Cycle

- Oxygen Compatibility
  - 6000 psi, 1000 deg F ox-rich steam (92 mol% O_2)
- High strength at temperature
  - 175 ksi at 850 deg F
- Creep resistant

Most High Strength Alloys Burn in High Pressure GOX



From Cliff Bampton, Boeing - Rocketdyne

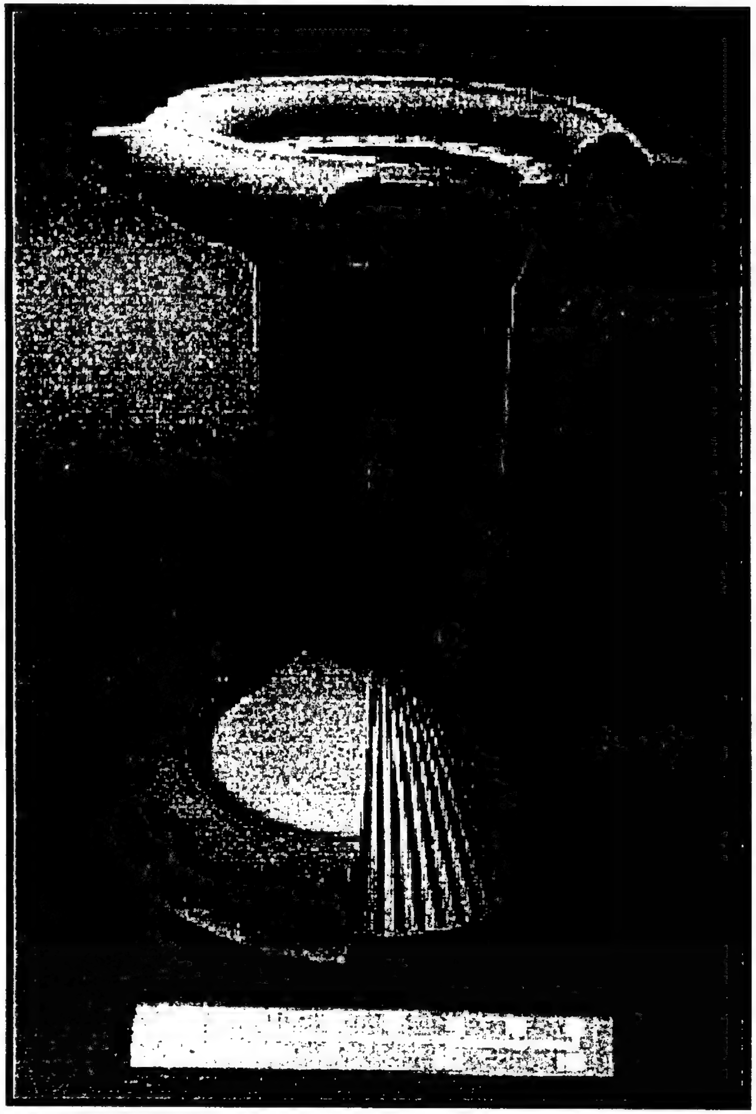
Full Flow Projects

- Nickel superalloy development
  - composition control for good oxygen compatibility and good structural performance

    RSC Ni superalloy effort

  - PM and casting process development
- Future potential projects
  - environmental barrier coatings development
  - nickel MMC

Typical Combustion Chamber



- Injector attaches at top
- Flow is from top to bottom
- Hot gas wall is copper alloy
- Structural Jacket and manifolds are high strength steel or nickel alloy
- Coolant channels contain high pressure (7000 psi) fuel (LH2)

Increased Combustion Pressures

- Greater need for cooling (heat flux greater than 100 btu/in^{2}sec)
  - transpiration cooling
  - extreme temperature gradients (6000 °F combustion temperatures, cryo coolant)

"Materials" Requirements for Transpiration Cooling

- Defined heat transfer rate
  - reliable structural performance at temperature with temperature gradient
- Controlled porosity
  - size of pores
  - density, density gradient
- Fabricatable into "hour-glass" shape (double curvature)

Current Transpiration Cooling Projects

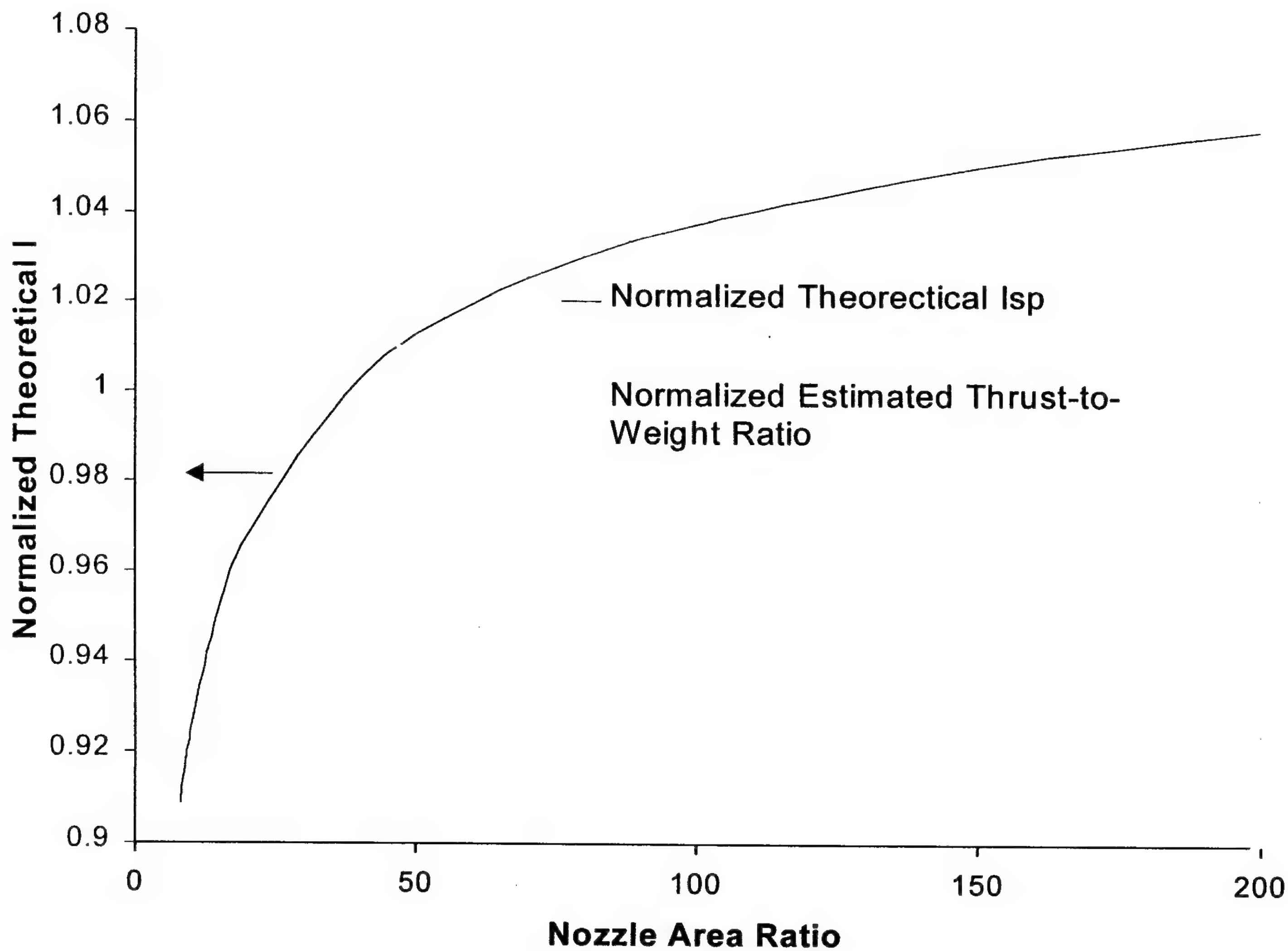
- Design optimization
  - analytical modeling and simulation effort
- Process and Fabrication efforts
  - "cool wall" copper liner
    - MRL = 4, PRL = 4, TRL = 2
  - "hot wall" concept
    - MRL = 1, PRL = 1, TRL = 1
- Future Efforts
  - small article demonstration testing

Higher Area Ratio Nozzles

- Ratio of throat area to exit plane area has a large influence on engine performance
- Influences engine weight with a practical size limit based on vehicle diameter

- Other Design Trades
  - amount of regenerative cooling
  - structural performance for side loads and gimbaling

Theoretical Engine Performance



“Materials” Requirements for Nozzles

- Resistance to chemical and thermal environment
  - actively or passively cooled
- “Reusability”
  - uncooled re-entry
  - replacement / repair
- Impermeability to exhaust gases
- Low density

Current Projects for Nozzles

- Exploratory effort for erosion-resistant high-temperature materials
- Future Efforts
  - engineering design trade studies
  - environmental protective coatings
  - potential expendable exit cone development
  - materials for high-stiffness nozzle concepts

Summary

- "Materials" development efforts are essential to achieving IHPRPT Phase II and III goals
  - engine system goals for performance, reliability, and cost
- Affordability is based on low production rate, high reliability, specialized components
- Ongoing and planned "materials" efforts
  - near net shape processes
  - composite engineering
  - design trade studies

Bibliography

- C. J. Meisl “Rocket Engine vs Jet Engine Comparison”, AIAA 92-3686, 28th Joint Propulsion Conference, July 6-8 1992, Nashville, TN (1992).
- J. C. Williams “Materials Requirements for High-Temperature Structures in the 21st Century”, Phil Trans Royal Soc London, 351 (1995) pp435-449.

Back up
Slides

IRLs and PRLs

- Creates a framework for judging material readiness for a particular application
  - application (component) specific
  - time frame specific

- Establishes uniform demonstration goals for material development and insertion
  - no specific route of progression implied
  - no assessment of degree of difficulty of progression

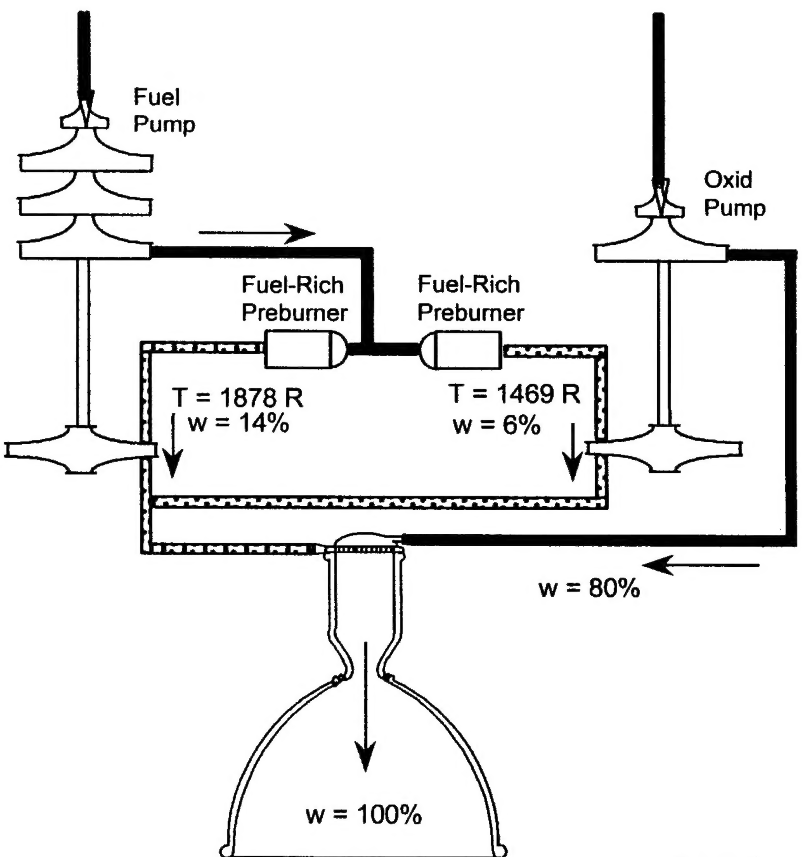
Aerospace Corp MRL and PRL

DEFINITIONS

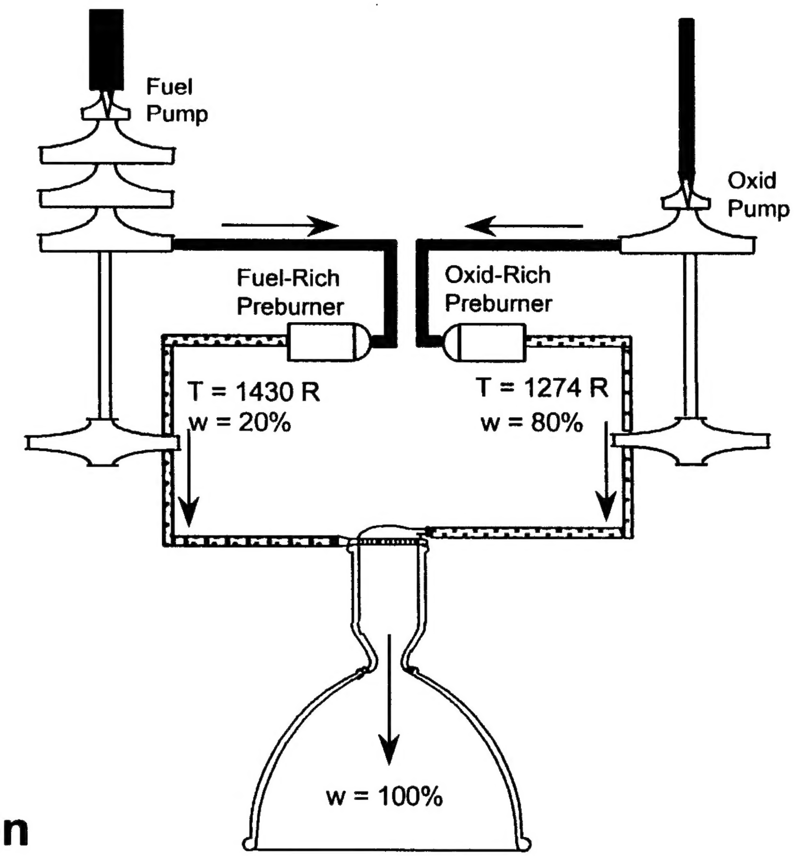
Materials Readiness Level (MRL)		Process Readiness Level (PRL)
Material routinely available and used in similar components	6	Process applied to object has produced defect free components; process parameter ranges identified
Material applied to shapes of the size and type of objective component with verified properties	5	Process has been applied to shapes of the size and type of the objective component.
Material applied to objective shape with verified properties	4	Process has been modified to apply to objective shape
Material data properties verified		Process produces desired physical and mechanical properties
Material within family identified		Process has been applied to simple test coupons
Material family/families identified		General classes of possible processes identified

Full Flow Cycle

Staged Combustion Cycle (SSME)



Full Flow Staged Combustion Cycle



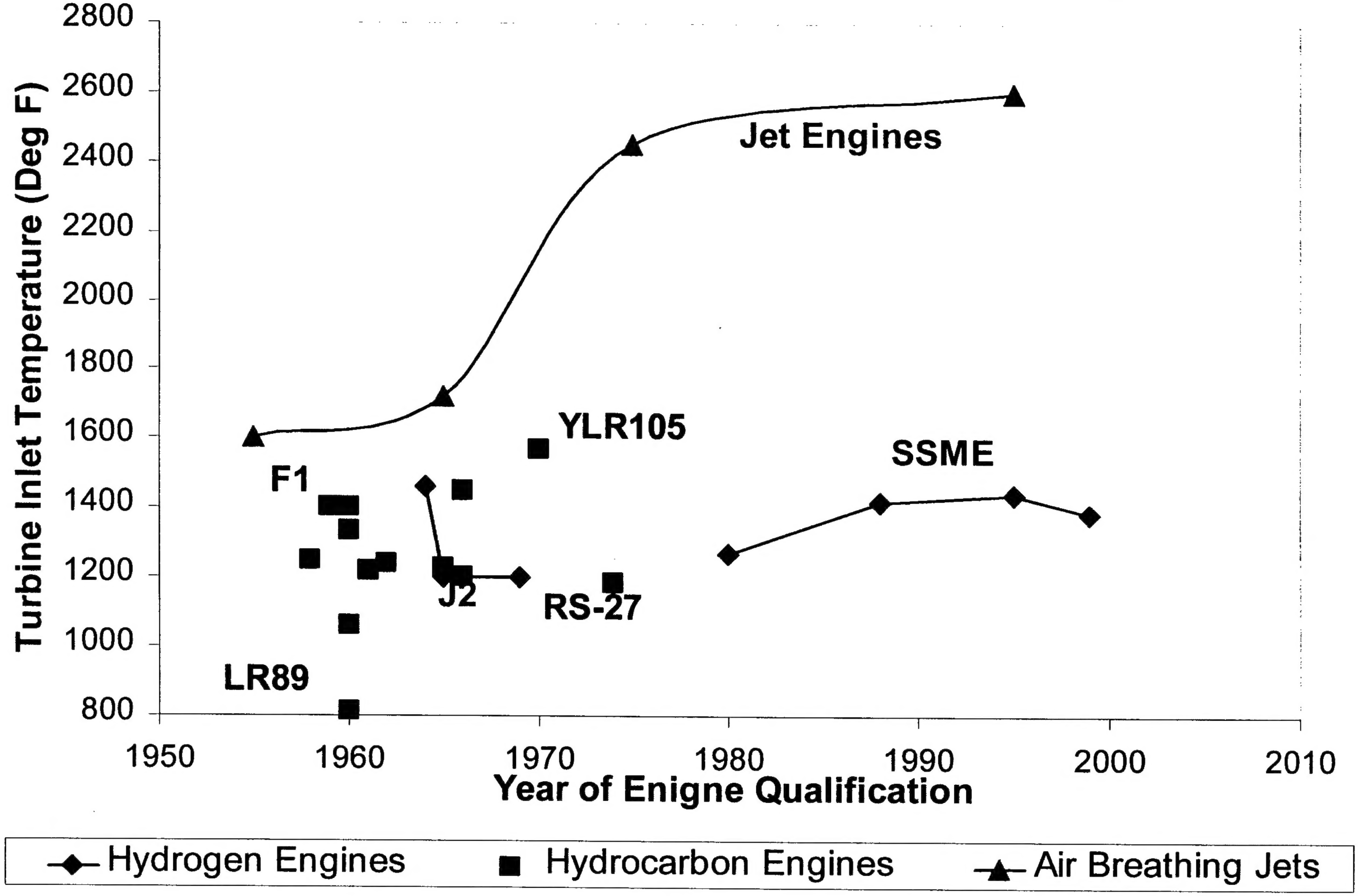
hydrogen
oxygen

Reduced Pump Stages

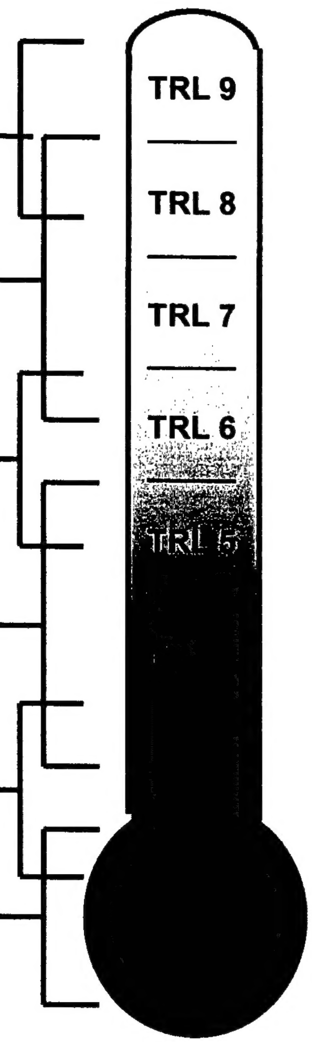
- Historical engines typically have 2 or 3 stage pumps
  - SSME has 2 pumps for each fuel and oxidizer
  - relies on forged and machined Titanium

- To meet IHPRPT goals
  - reduce parts count
  - reduce complexity
  - remove a pump stage while increasing discharge pressure

Liquid Rockets Engines Face Great Materials Challenge



NASA Technical Readiness Levels



System Test, Launch & Operations

System/Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

Actual system "flight proven" through successful mission operations

Actual system completed and "flight qualified" through test and demonstration (ground or flight)

System prototype demonstration in a space environment

System/subsystem model or prototype demonstration in a relevant environment (ground or space)

Component and/or breadboard validation in relevant environment

Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

Technology concept and/or application formulated

Basic principal observed and reported